TITLE: Resonant Parametric Generation of Infrared Radiation on Intersubband Transitions in Low-Dimensional Semiconductor Heterostructures

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Resonant parametric generation of infrared radiation on intersubband transitions in low-dimensional semiconductor heterostructures

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Abstract. A new scheme for generation of coherent radiation on the intersubband transition without population inversion between subbands is presented. The scheme is based on the resonant nonlinear mixing of the optical laser fields on the two interband transitions which are generated in the same active region and serve as a coherent drive for the infrared field. This mechanism for frequency self-conversion can work efficiently at room temperature and with injection current pumping. Due to the parametric nature of infrared generation, the proposed inversionless scheme is especially promising for long-wavelength (far-infrared) operation.

Introduction

Lasing on the intraband transitions between levels of dimensional quantization in quantum-well (QW) and quantum-dot heterostructures is a promising way towards injection-pumped laser generating in the mid- and far-infrared range (denoted below as IR for brevity). There are however two major problems. The first one is strong non-resonant losses of the IR field due to free-carrier absorption and diffraction, which become increasingly important at longer far-IR wavelengths. Second, due to very short lifetime of excited states it is difficult to maintain a large enough population inversion and high gain at the intersubband transitions, necessary to overcome losses. There were many suggestions to solve this problem by rapid depletion of the lower lasing state using, e.g., the resonant tunneling to adjacent semiconductor layers or transition to yet lower subbands due to phonon emission [1], or even stimulated interband recombination [2]. The successful culmination of these studies is the realization of quantum cascade lasers [3], in which the lower lasing state is depopulated either by tunneling in the superlattice or due to transition to lower-lying levels separated from the lasing state by nearly the energy of a LO-phonon.

We put forward another possibility [4], allowing us to achieve IR generation without population inversion at the intraband transition. This becomes possible with the aid of laser fields simultaneously generated at the *interband* transitions (called optical fields for brevity), which serve as the coherent drive for the frequency down-conversion to the IR. Employing self-generated optical lasing fields provides the possibility of injection current pumping and also removes the problems associated with external drive (beam overlap, drive absorption, spatial inhomogeneity), which were inherent in previous works on parametric down-conversion in semiconductors.

1. Generic three-level scheme

As the simplest case, consider the situation when only three levels of dimensional quantization are involved in generation: one (lowest-lying) heavy-hole level, and two electron

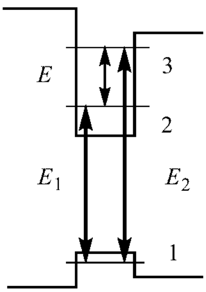

Fig. 1. Generic level scheme for three-color generation in an asymmetric quantum well: two strong fields E_1 and E_2 lasing at adjacent interband transitions $2 \to 1$ and $3 \to 1$ generate coherent IR radiation E at the beat frequency.

levels; see Fig. 1. Of course, this scheme also describes the situation when there are two hole levels and one electron level involved.

We need all three transitions to be allowed by selection rules. In a QW this will generally require using asymmetric structures, e.g. rectangular well with different barrier heights. Our calculations for asymmetric AlGaAs/GaAs structures based on the Kane model show that it is relatively easy to obtain the ratio of dipole moments of $e1 - hh1$ and $e2 - hh1$ transitions close to 3 for a wide range of parameters. Symmetric QWs can also be employed, e.g., under a strong DC field bias or in the case of a strong coupling between different subbands of heavy and light holes. In quantum dots the three-level scheme can be easily realized with all three transitions allowed.

When the injection current density reaches the threshold value $j_{\rm th}$, optical generation starts between ground electron and hole states. Upon increasing the pumping current, optical generation can start also from excited states and the laser can be completely switched to lasing from the excited state which has higher maximum gain due to a larger density of states. The effect of excited-state lasing was studied both in QW and QD lasers [5–7]. It was found that with optimized laser parameters the region of simultaneous ground-state and excited-state lasing can be around $j \sim 2j_{\rm th}$ [5, 6].

The presence of one or two strong optical driving fields in the cavity gives rise to a rich variety of *resonant* coupling mechanisms by which the IR field can be produced. Here we will concentrate on one such scheme in which the two coherent optical fields having frequencies ω_1 and ω_2 excite the induced electronic oscillations at the difference frequency $\omega = \omega_2 - \omega_1$. It is important to note that the coherent IR polarization is parametrically excited independently on the sign of population difference at the IR transition.

To maximize the IR output, the phase matching condition must be satisfied. This requires special waveguide design since refractive indices of bulk semiconductor materials for optical and IR frequencies are different. This issue is discussed elsewhere. Basically, one needs separate confinement layers of the IR and optical modes. For far-IR generation, there is more flexibility due to more efficient manipulation of the refractive index by doping.

2. Efficiency of IR generation

To quantify the above ideas, we have calculated the excited IR polarization and field by solving the coupled electronic density-matrix equations and electromagnetic Maxwell equations for the three fields, assuming steady-state generation.

In the case of homogeneous broadening, one can obtain analytic expression for the IR intensity $|\mathcal{E}|^2$:

$$|\mathcal{E}|^2 \simeq |\mathcal{E}_1|^2 \frac{|\mathcal{E}_2|^2}{|\mathcal{E}_2|_s^2} \left(\frac{d}{d_1} \frac{\omega}{\omega_1} \frac{\kappa_1}{G_1} \frac{G}{\kappa} \right)^2 + |\mathcal{E}_2|^2 \frac{|\mathcal{E}_1|^2}{|\mathcal{E}_1|_s^2} \left(\frac{d}{d_2} \frac{\omega}{\omega_2} \frac{\kappa_2}{G_2} \frac{G}{\kappa} \right)^2, \qquad (1)$$

Here the quantities without indices and with indices 1,2 correspond to the intersubband transition and to the interband transitions, respectively; d's are the dipole moments of the transitions; κ's and G's are the material losses and optical confinement factors of the waveguide modes; $|\mathcal{E}_{1,2}|_s^2$ are the saturation intensities.

At a given wavelength, the crucial parameter in the above equation which governs the efficiency of down-conversion, is $\eta = (\kappa_{1,2}/G_{1,2})(G/\kappa)$. The main source of IR losses is free-carrier absorption in the active region and doped cladding layers. Our detailed calculations for the GaAs-based structure with separate confinement of IR ($\lambda = 8$ μm) and optical modes ($\lambda = 0.73$ and 0.8 μm) yield the value of η around 0.5–0.8.

In the opposite limiting case of very large inhomogeneous broadening, we will assume that the inhomogeneous widths u_{ik} of all transitions are much larger than all homogeneous bandwidths γ_{ik}. In this case the precise shape of the inhomogeneous line is not important and explicit analytic formulas can be obtained for two different situations: when the optical field intensities are much smaller or much greater than the saturation values. Detailed analysis [4] shows that the IR intensity grows rapidly as the product of optical intensities generated on the interband transitions,

$$|\mathcal{E}|^2 \simeq |\mathcal{E}_1|^2 \frac{|\mathcal{E}_2|^2}{|\mathcal{E}_2|_s^2} \left(\frac{2\gamma_{32}}{(\gamma_{32}+\gamma_{21})} \frac{d}{d_1} \frac{\omega}{\omega_1} \frac{u_{21}}{u_{32}} \frac{\kappa_1}{G_1} \frac{G}{\kappa} \right)^2, \tag{2}$$

until it reaches the saturation value. Above this value, the IR field begins to deplete the electron populations, and its growth becomes nonlinearly saturated. In the optimal case, the maximum internal efficiency of the down-conversion can reach the limiting quantum value corresponding to one IR photon per one optical photon.

For the mid-IR range $5-10$ μm the maximum IR power is of order 10 mW if we have the value of 100 cm^{-1} for IR losses, and the optical field intensities inside the cavity are of the order of saturation values. Here we assumed $\eta \sim 0.1$. Beyond the reststrahlen region of strong phonon dispersion ($\lambda \geq 50$ μm for AlGaAs/GaAs structure) the expected IR power is ≤ 1 mW due to rapidly growing losses.

3. Conclusions

Our calculations demonstrate the generation of coherent IR emission at intersubband transitions due to nonlinear wave mixing in standard multiple QW or QD laser diodes. The prerequisite for this is simultaneous lasing at two optical wavelengths which provide the necessary drive fields. This mechanism does not require population inversion at the IR transition, and its threshold current is determined by the minimum injection current necessary for the interband lasing from higher (excited) carrier states of dimensional quantization.

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